

Long-term desalinated water demand and investment requirements: a case study of Riyadh

O. K. M. Ouda, Y. Khalid, A. H. Ajbar, M. Rehan, K. Shahzad, I. Wazeer and A. S. Nizami

ABSTRACT

The Kingdom of Saudi Arabia (KSA) is situated in an arid region and faces a chronic challenge to meet its increasing water demand. Riyadh is the capital of KSA and home to about six million people. The water demand is mostly met by groundwater resources (up to 48%), while the desalination plants cover the rest of the water supply requirements. There is a potential risk of a significant gap in water demand–supply due to the retirement of old desalination plants. This study, therefore, developed a probabilistic model to forecast desalinated water demand in Riyadh for domestic purposes up to the year 2040 based on three scenarios: low growth, the most likely (mean), and high growth scenario. The results showed that an investment of about US\$6.24, 11.59, and 16.04 billion is required to meet the future domestic water demand of the city for the next 25 years based on low, mean, and high growth scenarios, respectively. Moreover, a strong commitment to public–private partnership is required to remove the fiscal budget burden related to the desalination along with public awareness campaigns to reduce per capita water consumption, upgrading the water tariff system and using renewable energy to run desalination plants.

Key words | desalination plant, groundwater resources, probabilistic model, water demand, water supply

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LIST OF ACRONYMS AND ABBREVIATIONS

ED	electro-dialysis	MOWE	Ministry of Water and Electricity
GHG	greenhouse gases	PPP	public–private partnership
HABs	harmful algal blooms	RAK	Ras-Al-Khair
KACARE	King Abdullah City of Atomic and Renewable Energy	RO	reverse osmosis
KSA	Kingdom of Saudi Arabia	SWCC	Saline Water Conversion Corporation
MED	multi-effect distillation	UFW	unaccounted-for-water
MCS	Monte Carlo simulation	VC	vapor compression
MIGD	million imperial gallons per day	WHO	World Health Organization
MSF	multistage flashing	WTE	waste-to-energy

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INTRODUCTION

Scarce water supply in the Middle East region is a strategic and chronic problem that can be traced back to the early

1970s (Allan 1997; UNDP 2013). The Kingdom of Saudi Arabia (KSA) struggles with water scarcity, as it is located in the driest spot of the Middle East and has extremely hot summers and dry winters (SGS 2012). The country has no perennial lakes or rivers; the only reliable natural water source for domestic water supply is groundwater (World Bank 2004; Ouda 2015). In 2010, the total natural water resources that could be used in the country for all purposes, including agriculture, industrial, commercial, and domestic was around 188 m³ per capita. This figure is far below the threshold limit of 500 m³ per capita per year, set by the World Health Organization (WHO) for water stress countries (Jagannathan *et al.* 2009; UNDP 2013).

An enormous socio-economic development has occurred in KSA over the last few decades, as a result of revenues generated from high crude oil production (World Bank 2005, 2010; Nizami *et al.* 2015a, 2015b; Shahzad *et al.* 2016). In the early 1970s, KSA's population was 7 million. By 2010 it had increased to around 27 million, with an average growth rate of 3.4% (Ismail & Nizami 2016; Nizami *et al.* 2016a, 2016b). Urbanization levels also increased from 50 to 80% during this period (CDSI 2010; Ouda *et al.* 2014; Nizami *et al.* 2017). Consequently, the water demand in all sectors of KSA rose substantially (Abderrahman 2001; Ouda 2014a, 2014b). The water demand–supply gap in 2010 was around 11.5 billion m³ (Table 1), which was mainly bridged by depletion of groundwater resources (UNDP 2013).

A significant increase in water demand by domestic, industrial, and agriculture sectors will exert additional pressure on water resources and challenge the socio-economic development plans of the KSA's government (Ouda *et al.* 2016). The government has considered desalination of seawater as a strategic option to meet the growing domestic water demand throughout the country (Al-Ibrahim 2013). Currently, around half of the domestic water demand in KSA is fulfilled by 30 different desalination plants (SWCC 2010, 2011). These desalination plants are developed in the Red Sea and the coast of the Arabian Gulf, under the authority of the Saline Water Conversion Corporation (SWCC) (SWCC 2010, 2011). The production capacity of these desalination plants has significantly increased from around 200 million m³/year in 1980 to around 1,050 million m³/year in 2010 (SWCC 2010, 2011; MWE 2012; Ouda 2015).

Table 1 | KSA sustainable water resources yields vs. water demand in 2010 (Ouda 2015)

Water resources sustainable yields	Quantity (million m ³ /year)
Groundwater	3,850
Surface water	1,300 ^a
Total conventional sources	5,150
Treated wastewater	240
Desalinated water	1,050
Total non-conventional sources ^b	1,290
Total water resource yields ^c	6,440
Water demand	
Domestic	2,063
Industrial	800
Agricultural	15,000
Total	17,863
Water demand vs. supply gap	11,423

^aVariable depending on rainfall pattern.

^bThe total non-conventional sources include desalinated water, and treated wastewater available in the country every year.

^cThe total water resource yield is the total for both conventional and non-conventional resources.

The future estimations of water demand are critical for water system planning and design, water utilities asset management, and water resources management. These forecasts, along with the role of demand management policies, become more critical in areas of scarce water supplies such as the city of Riyadh (Almutaz *et al.* 2012; Rahmanian *et al.* 2015). However, despite the extreme importance of water forecasting, there is a very limited amount of literature and data available in KSA that tackles this topic. In fact, the little that exists is mostly outdated (Almutaz *et al.* 2013). The scientific literature documents various models for water demand forecast based on deterministic or probabilistic approaches (Arbues *et al.* 2003; Davis 2003; Worthington & Hoffman 2007; Alshawaf 2008). The selection of a forecast model is driven mainly by the data quality and its level of certainty. The deterministic model will be very efficient when the data are both high quality with high certainty levels (Cheng & Chang 2011). However, in situations where the main explanatory factors or variables are uncertain, the effectiveness of such deterministic models will be limited (Khatri & Vairavamoorthy 2009). This applies in particular for countries like KSA, where the temperature is the only variable (Almutaz *et al.* 2012). Other

potential explanatory variables are categorized by a high degree of uncertainties, including population, family income and housing growth rate, immigration, rigorous water pricing policy, and the inefficient management of the unaccounted-for-water (UFW) (Almutaz *et al.* 2013). All these factors make the probabilistic model approach more suitable than a deterministic model for KSA in providing a long-term forecast of water demand and associated investment requirements.

A sustainable water policy for Riyadh city requires an assessment of the long-term water desalination demand for domestic purposes, using a probabilistic model approach to implementing appropriate capital expenditures and develop new plans. Therefore, this study aims to determine the long-term investment needs for seawater desalination in Riyadh city for the next 25 years to meet the domestic water supply, with an ambition to maintain a sustainable water supply through a network of desalination plants. The study includes, in particular, the forecast of Riyadh's water domestic water demands up to the year 2040, assessment of the water supply options to meet the demands, suggestions for the appropriate desalination technologies based on the current practices and standards, and estimations of the necessarily required investments.

Case study – Riyadh city

Riyadh city has a population of about six million which constitutes more than one-fifth of the total population of KSA (CDSI 2014). The city has a very harsh climate with an average temperature ranging from about 8 °C in winter to 43 °C in summer. The annual evapotranspiration and wind speed vary from 1,168 to 979 mm and 6.5 to 13.9 km/hr, respectively. Humidity and annual rainfall vary from 15 to 51% and about 101 mm, respectively (SGS 2012; CDSI 2014; Al-Zahrani *et al.* 2015). Due to being a capital and an important industrial center, the city has witnessed a rapid growth in population and socio-economic development during the last few decades that has exerted tremendous pressure on the city's water resources (Ouda 2015).

The water supply for Riyadh city comes from local groundwater (about 48%) and desalination plants (about 50%) that are installed on the Arabian Gulf, about 450 km to the east of the city (Almutaz *et al.* 2013). The remaining

minimal amount (about 2%) comes from treated wastewater that is only used for landscape irrigation (Almutaz *et al.* 2012; Miandad *et al.* 2016a; Khan *et al.* 2017). The groundwater is produced from the shallow aquifer around Wadi Hanifa and its tributaries, and the deep wells of the Minjur and Wasia-Biyadh aquifers (Al-Mutaz 1987). The groundwater extraction rate was around 29.2 million m³ in 1964 and increased to around 4,369 million m³ in 2011 (Al-Mutaz 1987; MWE 2011, 2012; Al-Zahrani *et al.* 2015). The agriculture sector consumes the majority of extracted groundwater, and only around 320 million m³ of groundwater is utilized in the domestic water supply (Ouda 2013).

In 2011, approximately 338 million m³ of desalinated water was supplied to Riyadh city from the following three desalination plants that are located in the Arabian Gulf:

- 1) Multistage flashing (MSF) plant I: Its operational commencement year was 1982, and it currently has a production capacity of 118,447 m³/day.
- 2) MSF plant II: Its operational commencement year was 1983, and it currently has a production capacity of 815,185 m³/day.
- 3) Reverse osmosis (RO) plant: its operational commencement year was 2002, and it currently has a production capacity of 78,182 m³/day (SWCC 2011).

In 2010, the cost of desalinated water production was US\$0.80/m³, and the cost of pumping and distributing desalinated water to the end user was about US\$1.2/m³ (SWCC 2010). The SWCC has been operating Ras Al-Khair (RAK) desalination plant since 2014. The plant is a hybrid desalination plant that combines both the MSF and RO technologies. The plant is located in RAK industrial city along the Arabian Gulf. On a daily basis, the plant produces 728,000 m³ of water that serves around 3.5 million people in Riyadh city. The project construction cost was approximate US\$7.2 billion (Water Technology 2015).

The residential water consumption per capita in Riyadh city was about 308 liters/day in 2010 (MOWE 2011). This value is larger than the consumption levels in many other developing countries, but still comparable with the consumption levels in other Middle East countries (Almutaz *et al.* 2012). A significant share of the city's water supply system (up to 30%) is also covered by large UFW (MOWE 2011). This is mainly due to leaks in distribution systems

that are present in old areas of the city. The cost of operating desalination plants and distribution of clean water to consumers is US\$2/m³. This price is extremely high, even though KSA uses its cheaply produced oil to meet the energy requirements of the desalination plants (Ouda 2013a). The cost of treating local groundwater is also high, estimated at US\$0.5/m³, while contribution cost is very low in comparison to desalinated water transportation cost, where water is pumped from the coastal area (about 400 km) to Riyadh city. The water as a commodity is virtually free throughout the country, as the government gives a huge subsidy on water consumption. Domestic consumers pay less than 5% of the production and distribution cost of water (Ouda 2013b). Consequently, water is significantly underpriced. This makes water demand artificially high and ultimately leads to inefficient use (Ouda 2015). Very recently, the KSA's government adopted a new water tariff for domestic water consumers. The new tariff raises the water cost for domestic consumer by almost 70%. It is worth noting that even with the new tariff, water is still heavily subsidized by the Saudi government and the new tariff impact on domestic water demand has not been realized as yet (Ouda 2015).

METHODOLOGY

Water demand forecast using probabilistic model

The development of a probabilistic forecast model for any city relies on the selection of explanatory variables followed by the assignment of probability density functions to each selected variable (Almutaz *et al.* 2012). The forecast time frame is set to the year 2040. This matches with the average useful life of a desalination plant which is 25 years. The average household income is the first selected explanatory variable (Table 2). In some countries, the water bills are a significant fraction of household income. However, in the case of KSA, where the government largely subsidizes water cost, the household income has a minimum indirect effect on water consumption. For example, higher income or wealth can be used for luxury goods such as dishwashing machines and swimming pools that lead to higher water consumption. Moreover, households with high income possess large houses that tend to consume larger quantities of

Table 2 | Mathematical expressions and forecasting model variables (Almutaz *et al.* 2012, 2013)

Mathematical expressions and models' variables

The total water use was estimated by the following standard functional population model: $Q_y = Nq$ where Q_y is the total annual water use in year (y), N the population at year (y), and q is the water use per capita

The water use (q) per capital was assumed to depend on the following explanatory variables:

$\ln q = a + b \log(\text{Income}) + c \log(\text{Household size}) + d \log(\text{Temp})$ whereas, income is the normal distribution with an average growth rate of 2.2%, while the standard deviation is restricted to 10% of the mean. Household size, including the average number of persons per household, is triangular probability distribution. The mean is assumed to increase by an annual growth rate of 2.4% from the base value of 5.86. The minimum and maximum values of $\pm 1.5\%$ of mean. Temperature is normal distribution with a standard of deviation of 1 °C

The model parameters were determined using @Risk. The population (N) forecast was based on the following methodology: The population growth rate is based on the data for annual growth rate for Saudi and non-Saudi population, currently the annual growth rate of Saudi's population is 2.95%, while it is 2.895 for non-Saudi's population. The change in annual growth rate of Saudi's population is 0.16%, while it is 0.26% for non-Saudi's population

Given the above nominal data, the growth rate of Saudi was computed (resp. non-Saudi) at year i through the following formula: Growth rate of Saudi at year i = Annual growth rate for Saudi - Change in growth rate for Saudi*(year i - reference year)

The total population of Saudi (resp. non-Saudi) at year i is then calculated by: Total population of Saudi at year i = Population at reference year*Exp. [growth rate of Saudi at year i *(year (i) - reference year)]

water. The average household income was assumed to be normally distributed with an average growth rate of 2.2%, while the standard deviation is restricted to 10% of the mean (Table 2).

The water forecast model also depends on population size and its growth. Riyadh city attracts both national and international immigrants. Immigration from outside the country, in particular, depends on the economic opportunities of the oil-rich country. The uncertainties incorporated in local population growth are therefore justified. Currently, the Saudi population is growing at an annual rate of 2.95% (Almutaz *et al.* 2013). Planning authorities predict a decline in population due to several socio-economic factors. Data from the Central Department of

Statistics indicate that the population growth rate will decrease with a mean value of 0.16%; minimum of 0.1% and a maximum of 0.25% (Almutaz *et al.* 2012). The current annual growth rate of 2.90% was assumed for the non-Saudi population. The authorities also predict a decrease in the flux of international immigrants, which will result in a decrease in the growth rate with a mean of 0.26%; a minimum of 0.2% and a maximum of 0.3%. The change in the growth rates is, therefore, best described by a triangular probability distribution that is based on three parameters, including mean, minimum, and maximum (Table 2). The household size and an average number of persons per household are other important explanatory variables. Data from the Central Department of Statistics indicate that the number of housing units will increase annually by a rate of 2.3% (Almutaz *et al.* 2012). Since the population growth was assumed to follow a triangular probability distribution, it seems logical that a similar distribution was selected for the household size. The parameters of the distribution were taken from the demographic forecast. The minimum and maximum values of $\pm 1.5\%$ of mean were taken for the triangular function, which was assumed to increase by an annual growth rate of 2.4% from the base value of 5.86 in 2011 (Table 2).

Temperature is an important explanatory variable for arid Riyadh city, as the temperature can change from 45 °C in summer to 5 °C in winter. The temperature is therefore expected to affect the water consumption significantly. The monthly mean of daily maximum temperature was the only weather variable selected in the predictive model. It was assumed to have a normal distribution with a standard deviation of 1 °C (Table 2). The probabilistic water forecast model also includes the effect of UFW and conservation measures. According to the data collected from the Ministry of Water and Electricity (MOWE), UFW accounts for 30% of total water production, 50% of residential, and the rest for non-residential purposes, including commercial and public sectors. The ministry has a long-term plan to reduce such high-current UFW levels to below 15%. However, only half of the current UFW is estimated to be the real loss (i.e., undetected network leakage and water meter deficiencies) that can be reduced by UFW management. Therefore, the actual target is to reduce the real loss down to 5% by 2041. These assumptions dictate setting the

expected UFW to 10% and restricting its possible values to between 0 and 20%. A triangular distribution having a mean of 10% and the minimum and maximum values between 0 and 20% is suitable for UFW. The surface water was not included in the water forecast model. The reasons for this are the little rain and whatever surface water is available is used only for agricultural purposes. Moreover, the dominant climatic features of the city are high temperature, low humidity, and hot winds resulting in high evaporation rates (Al-Saud 2010).

The water conservation measures that are planned in the city include the replacement of a number of current fixtures with more efficient ones. A target of 90% is set for new fixtures by 2041. The most likely set of assumptions, among many different assumptions examined, resulted in a range of 20–25% reduction. A uniform distribution is chosen to account for such water conservation measures. The upper and lower ranges of this distribution were set to remain within 20% of the average annual savings of 5% (Almutaz *et al.* 2012, 2013). After forming the forecast model, Monte Carlo simulation (MCS) was employed to determine the point demand model with specified variable uncertainties, which made a probabilistic demand model to obtain the total water consumption distribution. The @Risk software package, version 6.0 by Palisade Corporation (www.palisade.com) was used to carry out the MCSs. This software can be used for a number of probability distribution functions. It allows the simulations to generate random numbers and specify sampling rules, together with setting graphics and other scenario options. A confidence interval of 90%, in which potential water demand would fall, was projected and formed with 5th and 95th percentile values. The 5th, 95th, and mean values roughly represent the low, high, and most likely growth scenarios, respectively.

Water demand–supply gap

The typical lifetime of a desalination plant ranges between 25 and 30 years, depending on the type of technology (Raluy *et al.* 2004). The existing old plants, if refurbished, will provide an additional 15 years' lifetime to the plant (Schiffler 2004). Accordingly, the useful life of a desalination plant was adopted to estimate the water demand–supply gap, while the gap in the water supply was assessed based

on an estimation of the available desalinated water quantity and the model feeding of future demand (Sommariva *et al.* 2001; IAEA 2002; Raluy *et al.* 2004). The water supply capacity of the existing desalination plant was calculated based on the following considerations.

In the years, 2023 and 2024, respectively, both desalination plants MSF I and MSF II will complete their lifetime with a total useful life of 40 years from the date of operation and will maintain the same production rate until complete amortization. Second, the amount of water, 906,600 m³/day, to be supplied by the local groundwater resources, was assumed to remain the same until the year 2040. The reason for this includes the ongoing debate on whether the groundwater in KSA can be considered as a renewable or not (Foster & Loucks 2006). If the groundwater is renewable, then an increasing use of groundwater will be assumed. While, if the groundwater is not considered as a renewable, then a decreasing use of groundwater will be assumed. Therefore, a constant supply of groundwater for the future was assumed until the year 2040. Third, the RAK plant (900,000 m³/day) will supply the desalinated water for a total duration of 40 years from the year 2014 onward. Fourth, the amount of water, 78,182 m³/day, to be supplied by RO plant, was also assumed to remain the same until the year 2040. Total water supply from 2012 until 2040 is shown in Figure 1. Initially, the water supply

for all scenarios was around 1,918,000 m³/day in 2011. This has been increased to 2,818,000 m³/day by 2014 due to the inclusion of the RAK plant. Afterwards, the water supplies will be reduced to the amount of 1,884,826 m³/day with the retirement of old MSF plants. This trend will remain constant until 2040.

Desalination technologies

The desalination technologies (Figure 2) are classified as thermal or membrane-based technologies. The membrane-based desalination technologies include RO and electrodialysis (ED), whereas the thermal based desalination technologies include MSF, vapor compression (VC), and multi-effect distillation (MED) (Al-Karaghoul & Kazmerski 2013). RO technology is a pressurized filtration process, where a semi-permeable membrane filter is used to allow only water to pass through (Figure 2). The products of RO are fresh water as well as a concentrated solution that remains on the membrane side with high pressure. The process is completed in four steps: (1) pretreatment, (2) high-pressure pump, (3) membrane, and (4) post-treatment. RO is widely used for the treatment of saline groundwater and seawater and can be expanded easily from house level to commercial scale (El-Dessouky & Ettouney 2002; Al-Karaghoul & Kazmerski 2013).



Figure 1 | Projected water supply for Riyadh up to year 2040.

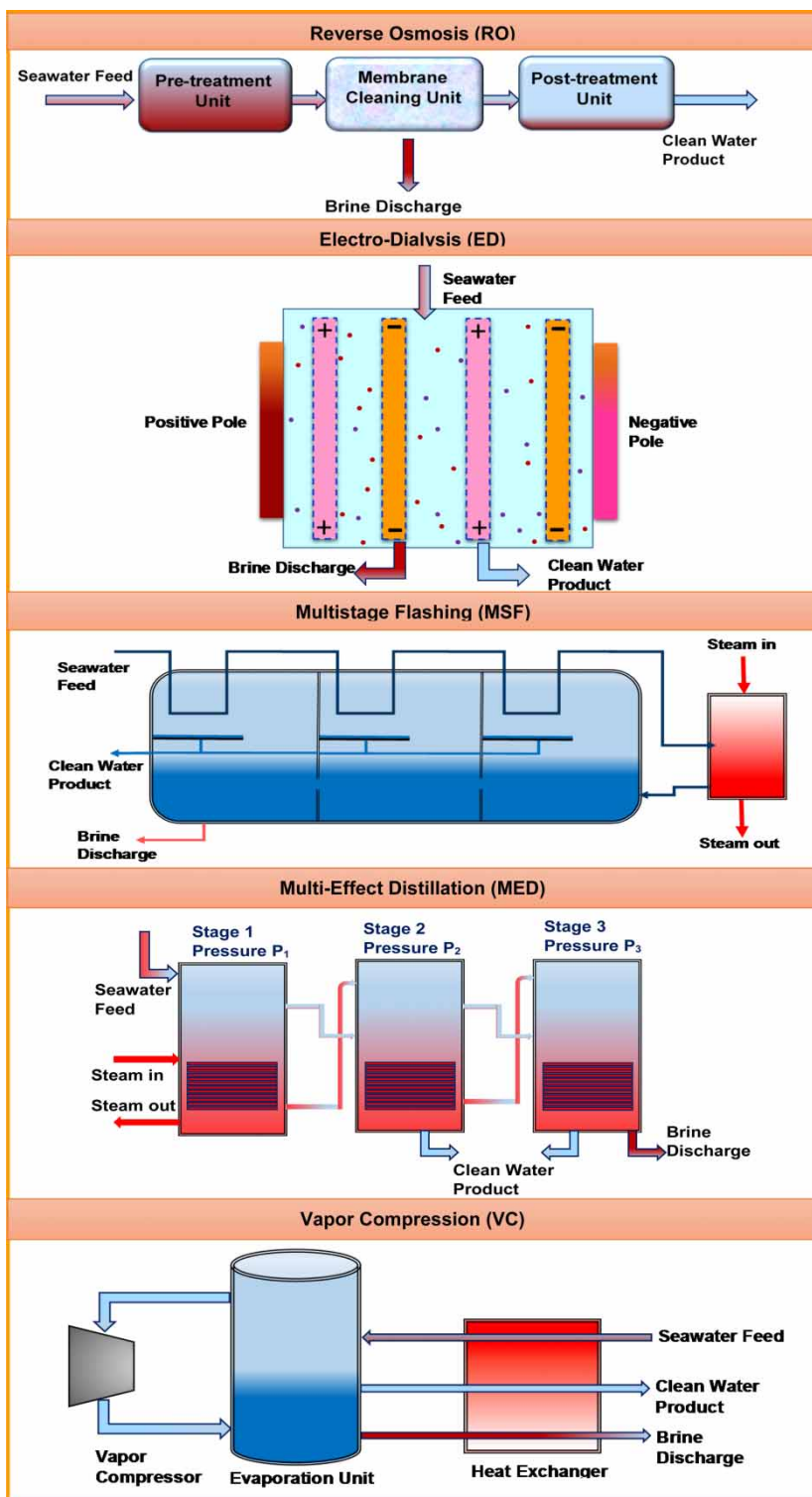


Figure 2 | Schematic diagrams of prominent desalination technologies.

ED uses a direct electrical current for the separation process, where salt ions are moved selectively through a membrane (Figure 2). The ED unit is completed with the following sub-systems: pretreatment system, low-pressure circulation pump, membranes stack, direct-current power supply, and post-treatment system (Strathmann 1992; Al-Karaghoul & Kazmerski 2013). MSF is an energy-intensive technology that needs both electrical and thermal energy for operation (Figure 2). The thermal energy, in the form of low-pressure and medium-pressure steam, is used to heat the feed-brine and ejectors for generation of required vacuum in different sections of the unit. Electrical energy is used to run other parts of the unit, including water cooling system, product distillation, brine blowdown, condensation and chemical dosing pumps. After RO, the MSF is the second most-used desalination technology worldwide (Al-Mutaz & Al-Namlah 2004; Al-Karaghoul & Kazmerski 2013).

The MED process is completed in a series of steps that are maintained at relatively lower pressure levels in comparison to other desalination technologies (Figure 2). At the first stage, the brine temperature is increased to around 70 °C by heat coming from one of many possible sources, including the waste heat from power plants, fossil fuel-based boiler, solar, or other heat sources in order to evaporate some of the brine left inside at the low pressure (Al-Mutaz & Al-Namlah 2004). In the second stage, the produced water vapors are transferred inside a tube for extra boiling that produces the water vapors in a series fashion.

The interest in the MED process in the last few decades has increased significantly, and it has gained a bigger market share (Al-Karaghoul & Kazmerski 2013). VC technology utilizes the heat produced by the compression of water vapors to evaporate salt water (Figure 2). The process is completed in two steps: thermo VC and mechanical VC. The feed water enters the VC process through a heat exchanger and generates water vapors in the evaporator. The water vapors are then compressed by mechanical or thermal compression methods (Al-Karaghoul & Kazmerski 2013). A comparison between the three dominant desalination technologies, including the MSF, MED, and RO is presented in Tables 3 and 4, based upon three sets of criteria: merits and limitations, computable (quantitative), and non-computable (qualitative) criteria.

RESULTS AND DISCUSSION

Water demand–supply gaps

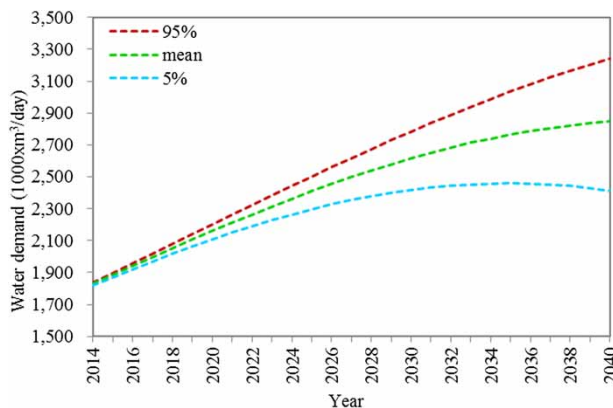
The results of water demand forecast for Riyadh city are presented in Figure 3, which shows the annual water demand for the 5th (low-growth scenario) and 95th (high-growth growth scenario) percentiles and the most likely scenario (the mean). The most likely projected water demand for the year 2040 will be about $2,846 \times 10^3 \text{ m}^3/\text{day}$. This value lies between the limits of $2,414 \times 10^3 \text{ m}^3/\text{day}$ (low-growth scenario) and $3,240 \times 10^3 \text{ m}^3/\text{day}$ for 95% (high-growth

Table 3 | Comparisons of selected desalination technologies based on their merits and limitations (Napoli & Rioux 2016)

	Detail	Merits	Limitations
MSF	Power source is combined-cycle gas turbine cogeneration	Maintenance and operational costs are lower	Capital cost is higher
		Sensitivity to salts is lower	Energy consumption is higher
MED	Power source is combined-cycle gas turbine cogeneration	Maintenance and operational costs are lower	Capital cost is higher
		Sensitivity to salts is lower	Energy consumption is higher
RO	Power source is electric grid	Energy consumption is overall low	Maintenance and operational costs are higher
			Membrane fouling due to HABs Under high salt concentrations and impurities, the process reliability is affected

Table 4 | Comparison among the dominant desalination technologies (Ghaffour et al. 2013; Mabrouk 2013; Al-Karaghoul & Kazmerski 2013)

Description	MSF	MED	RO
Non-computable (qualitative) criteria			
Maintenance and reliability	High	High	Average
Power generation dependency	High	High	Low
Robustness	High	High	Less than MSF
Future technology options	Low	Average	High
Flexibility	Low	Average	High
Environmental impact	High	High	Low
Feed water sensitivity	Low	Low	High
Computable criteria (based upon 15 MIGD (68,184 m ³ /day) plant)			
Description	MSF	MED	RO
Unit operating cost (US \$/m ³)	1.07	0.83	0.76
Annual operating cost ^a (US\$ million/year)	26.63	20.656	18.92
Operating cost (OPEX) ^b (25 years) (US\$ million)	665.75	516.5	475
Capital cost (CAPEX) ^c (US\$ million)	(9 × 15) = 135	(8 × 15) = 120	(7.5 × 15) = 112.5
Total cost (US\$ million)	800.75	636.5	585.5

^aAnnual operating cost = (Unit operating cost) (Plant capacity).^bOPEX = (Annual operating cost) (25 years); (Plant life cycle is considered to be 25 years (Mabrouk 2013).^cCAPEX = (Unit capital cost) (Plant capacity).**Figure 3** | Projected water demand for Riyadh up to year 2040.

scenario). The above-mentioned projected water demand can also be calculated using the water deficit between available water supplies and projected demand.

The total water demand–supply gaps for all three scenarios are presented under two different time period zones, as shown in Figure 4. During the first time period zone, the water supply would meet the water demand, whereas the water demand will exceed the water supply during the second time period zone. This change will start from the year 2024, where the demand and supply curves intersect with each other, as shown by an arrow in Figure 4. The water deficit for 2024 was 30% for a 95% demand scenario that increased to 72% (about 1,366 thousand m³/day) in 2040. Similarly, there will be a water deficit of 20% in 2024 for a 5% demand scenario that further increased to 28% (531 thousand m³/day) in 2040. Regarding the mean (the most likely scenario), the deficit value for 2024 is 25%, increasing to 51% (981 thousand m³/day) by 2040 (Figure 4).

Suitable desalination technologies

In cross comparison (Tables 3, 4 and Figure 2), RO is preferred over MED and MSF, as there is a better understanding today of the pretreatment requirements of the RO process. However, RO's ability to handle feed-in seawater with variable quality is still a major drawback. This is particularly the case for Arabian Gulf water with high level of harmful algal blooms (HABs) and salt concentration. The HABs tend to cause membrane fouling with an accumulation of organic and particulate materials and, ultimately, results in operational problems of the RO plants. On the other hand, high thermal efficiencies, savings in fuel costs, operation at a low temperature to avoid corrosion and scaling, and ability to operate with feed-water that has a large salt concentration are some of the advantages of the MED process (Tables 3 and 4). However, in many cases, and specifically for larger plants, the lowest cost is obtained by MED when joining power and water production (Tables 3 and 4).

Seawater desalination together with power generation provides a promising and better usage of fuel (Ouda 2015, 2016). In this regard, MSF desalination plants can allow cogeneration of water and electricity. Therefore, the cost of the plant can be distributed to products such as water and electricity, if power generation is considered from MSF (Tables 3 and 4); although the unit operating

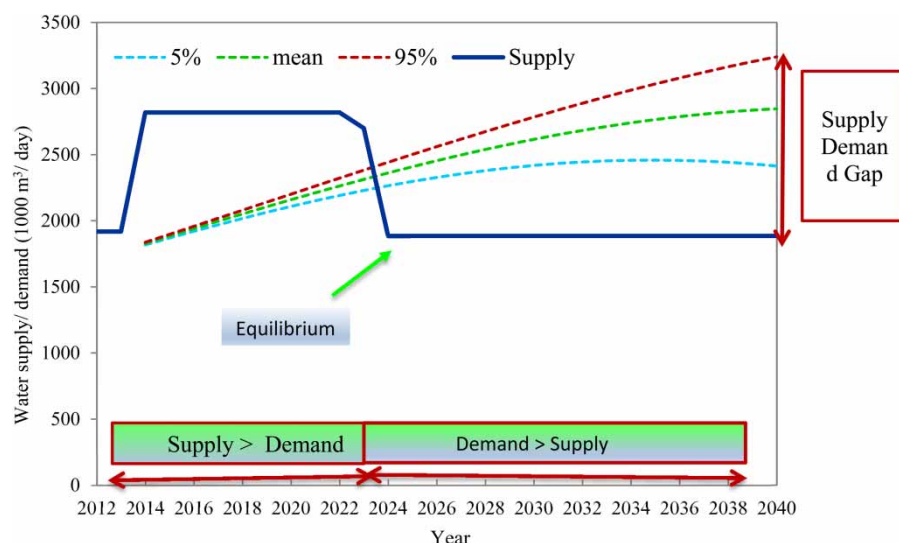


Figure 4 | Projected demand–supply curve for three scenarios up to year 2040.

(US\$1.07/m³) and annual operating (US\$26.6 million) costs of MSF are relatively higher than MED and RO's unit operating (US\$0.83 and 0.76/m³) and annual operating costs (US\$20.66 and 18.92 million), respectively (Table 4). Considering each plant life cycle to be 25 years, the total cost of MSF plants would be about US\$800.75 million as compared to US\$636.5 and 585.5 million for MED and RO desalination plants, respectively. However, the proven track record reliability of operation over a longer period of time (more than 30 years) coupled with construction in large capacities are special features that give added advantages to MSF plants than RO and MED desalination plants (Almutaz *et al.* 2012, 2013). MSF, therefore, is a commercially viable and dominant desalination technology in the Middle East region, with a market share of about 70% (Mabrouk 2013). Moreover, MSF plants provide a significant benefit in reusing the old MSF plants' infrastructures in building new similar plants. The MSF operation is also slightly influenced by the feed-in water quality (Table 4). Therefore, MSF will provide more technical and economic advantages for serving Riyadh city's desalination needs to fulfill the water deficit for years to come.

Advances in technology and the maximum number of running units determine the size and number of units for respective desalination technologies. In comparison, only MSF units are becoming bigger in size and unit capacity (Table 4). The RAK desalination plant is one of the latest

plants, with a unit size of 16.7 million imperial gallons per day (MIGD) that is equivalent to 75,898 m³/day. Therefore, it was assumed as a benchmark for developing new desalination units, as it is of good standard size and proven to work for a longer period of time in KSA (Water Technology 2015). The location of desalination plants is very critical. According to Tsiourtis (2008), a plant should be developed in an area where interconnections to power and water supply networks are technically possible and economically affordable. In this regard, the current infrastructure of roads can be utilized along with existing fuel network facilities.

Economic analysis

Due to the extra advantages, the total investment required and detailed economic analysis for the next 25 years was carried out only for MSF desalination technology. The overall capital and operational costs of any desalination plant depend upon many factors, including feed water features, quality of produced water, plant capacity, local conditions and labor costs, and energy sources and requirements. A single unit of 75,898 m³/day capacity was selected as a benchmark capacity for MSF evaporators. The annual operating cost of US\$29.64 million for each MSF unit included the cost of parts (US\$0.01/m³), chemicals (US\$0.05/m³), labor (US\$0.08/m³), amortized capital cost (US\$0.42/m³), thermal energy (US\$0.31/m³), electrical energy (US\$0.20/m³), and

unit operating cost (US\$1.07/m³) in the economic analysis (Table 5). The capital cost (CAPEX) of the same MSF unit would be about US\$150.3 million. So each MSF unit would require a total investment of US\$891.3 million due to CAPEX (US\$150.3 million) and operating costs (OPEX) (US\$741 million) based on the plant life of 25 years.

Based on this, MSF desalination costs (Table 5) and the water demand–supply data, the required total investments for the three scenarios were calculated and are summarized in Table 5. Considering the three water demand forecast scenarios of low, mean, and high, the water demand of 531,000, 981,000, and 1,366,000 m³/day, respectively, was predicted for Riyadh city for the next 25 years. To meet this demand for all three scenarios, 7, 13, or 18 MSF units, respectively, would need to be installed in Riyadh city (Table 5). As the total cost of each MSF unit was estimated to be US\$891.3 million, the KSA government would need to invest about 6.24, 11.59, and 16.04 billion US\$ to meet the future water demand of Riyadh city through MSF desalination technology for the next 25 years, based on low, mean, and high water demand scenarios, respectively (Table 6).

This is a substantial amount of money, given the country's high dependency on crude oil revenue and the drastic decrease in crude oil prices (Demirbas *et al.* 2016a, 2016b, 2016c). Furthermore, the public has very little knowledge about the water shortage in the country and other related

Table 6 | Number of units (based on 75,898 m³/day unit capacity) and total cost

Demand forecast scenario	Predicted water deficit (thousand m ³ /day)	Number of units	Total investment (US\$ billion)
5%	531	7	6.24
Mean	987	13	11.59
95%	1366	18	16.04

challenges, including the cost of water production and distribution, and the government's huge subsidies (Ouda *et al.* 2013; Ouda 2014b). These conditions diminish the potential for water conservation and put the operational productivity and financial stability of the water desalination plants at stake (Ouda 2015). Therefore, there is a high need for long-lasting and effective awareness campaigns among communities and institutions for promoting water conservation in the country (Ouda 2015).

Desalination technologies and climate change

The impact of desalination technologies on climate change and how the research and development trends influence the overall water management systems with time must be considered in water policy-making models (Table 7). Currently, desalination process for cleaning water is one of the most energy-intensive processes and consumes more energy for producing each liter of water than most other water treatment and supply methods in KSA (Ouda 2015). For example, in RO desalination technology, around 70% of total energy intake is by the RO process, and the remaining 30% is consumed for water pumping and pre- and post-treatments. Desalination plants use around 15,000 kWh per million gallons or 4 kWh per m³ of water produced (Foster & Loucks 2006). However, these estimated energy consumption values are based on a fixed set of conditions in ideal scenarios, but the actual operating conditions are usually not so ideal due to various process limitations and losses (Napoli & Rioux 2016). In KSA, currently, the energy consumed by desalination plants is mainly generated by fossil fuels that result in greenhouse gas (GHG) emissions and potential climate change (Table 7).

Since the understanding of challenges and risks associated with climate change for ecosystems and human

Table 5 | Cost summary for the 75,898 m³/day MSF plant, adapted from GWI/WDR (2012), Al-Karaghoulis & Kazmerski (2013), Wilf *et al.* (2007), and Banat (2007)

Description	Units	Cost ^a
Parts	US\$/m ³	0.01
Chemicals	US\$/m ³	0.05
Labor	US\$/m ³	0.08
Amortized capital cost	US\$/m ³	0.42
Thermal energy	US\$/m ³	0.31
Electrical energy	US\$/m ³	0.20
Unit operating cost	US\$/m ³	1.07
Annual operating cost for 75,898 m ³ /day	US\$ million/year	29.64
Operating cost (OPEX) (25 years)	US\$ million	741
Capital costs (CAPEX)	US\$ million	150.3
Total cost (CAPEX + OPEX)	US\$ million	891.3

^aCost is based on an oil price of US\$60 per barrel (GWI 2012).

Table 7 | The recommendations and future perspectives of water management in KSA

Recommendations	
1	One of the most obvious recommendations would be to make all possible efforts for maximum water conservation, including moving towards more efficient systems and reducing the current huge government water subsidies
2	The negative impact of current desalination processes due to high energy consumption and brine disposal on local environment should be studied, aimed at helping reduce water consumption and moving towards more sustainable and environment friendly technologies
3	Currently, KSA desalination processes are running on non-renewable fossil fuel-based energy leading to negative environmental impact. The possibilities and sustainability of using renewable energy including water-to-energy should be investigated
4	More funding should be allocated for research and development work, to reduce the cost of clean water and negative environmental impact of desalination technologies, and to study feed water pre-treatment, sustainable ways of managing brine and other waste, more energy efficient systems and potential of combinations of renewable energy and distillation technologies
5	All stakeholders including academics, environmentalists, policy-makers, government institutions, etc. should collaborate with each other to tackle this serious worldwide issue of clean water production and distribution
6	Public awareness, concerning the importance of sensible water usage and the challenges and costs associated with cleaning and distribution of clean water, should be created through seminars, education, media, and public events
7	The recent advancements and emerging trends in desalination technologies, especially in design and development of renewable energy powered desalination plants, can significantly reduce GHG emissions and their impact on climate change

well-being is increasing with time, so does the importance of energy sources, consumption, and GHG emissions grow (Foster & Loucks 2006; Shahzad *et al.* 2015; Miandad *et al.* 2016c). The recent advancements in desalination technologies and emerging trends in design and development of renewable energy powered desalination plants can significantly reduce GHG emissions and their impact on climate change (Table 7). KSA's government has recently launched a special program, the King Abdullah City for Atomic and Renewable Energy (KACARE) to generate about 72 GWe from renewable energy sources, including nuclear, solar, the wind, waste-to-energy (WTE), and geothermal, by 2032

(Nizami *et al.* 2015a; Demirbas *et al.* 2016a; Miandad *et al.* 2016b; Rehan *et al.* 2016; Sadeh *et al.* 2016). Moreover, other important factors to reduce the climate change effect should also be considered in water management policy-making and implementation, including reducing the per capita water consumption and improving infrastructure and water reuse in the country (Napoli & Rioux 2016).

Future perspective

The ongoing slump in global oil prices is changing the way governments and economies in the Middle East work, and water is no exception to the trend. In the petro-economies that make up some of the world's biggest markets for desalination, such as KSA, Iran, Qatar, and Abu Dhabi, oil-driven national budgets have been savaged by an oil price that has decreased to less than half over the last 12 months. Moreover, the dwindling water supplies and uprising water demand has adversely affected the mega cities around the world in general and KSA in particular (Ouda 2015). Riyadh, being KSA's most densely populated city consumes an incredible amount of water per day. The bulk of desalinated water is supplied through desalination plants located in the Eastern Province of KSA (Almutaz *et al.* 2012). The older plants will complete their lifespans in the near future, and there will be a huge water deficit once these plants stop working (Almutaz *et al.* 2013). In this regard, the present study presents a foundation for selecting the most suitable desalination technologies. MSF technology seems to be a promising choice to fulfill Riyadh city's desalination needs. However, the determinations of water demand and water forecast are critical and challenging tasks due to the uncertainties in population and economic growth coupled with fluctuations in international crude oil prices. Finally, research initiatives towards improving desalination technology efficiency and minimizing its potential environmental impacts are greatly needed (Table 7). Nonetheless, the decision to implement any desalination technology needs further in-depth technical, economic, social, and environmental investigations using life-cycle assessment and life-cycle thinking methodologies (Nizami & Ismail 2013; Nizami *et al.* 2014, 2016b; Rathore *et al.* 2016). KSA should take the lead in this aspect, given the country's high dependency on desalination plants for domestic water usage.

CONCLUSIONS

This study has presented a case for Riyadh city to estimate its long-term desalination needs. A probabilistic approach with three scenarios: low growth, most likely (mean), and high growth was used. The gaps between the available water resources and total water demand for up to the year 2040 for the three scenarios were estimated, along with required investments. The analysis showed that KSA needs to invest about US\$6.24, 11.59, and 16.04 billion on low, mean, and high-growth scenarios, respectively, to meet the future water demand of Riyadh city for the next 25 years. These findings will help the policy- and decision-makers and water authorities to not only better understand the water demand and supply situations, but also facilitate in taking decisions to build new desalination plants to cope with predicted water shortage problems. Additionally, governments need comprehensive initiatives to improve the desalination industry's long-term financial sustainability and encourage public-private partnerships (PPP) to remove the fiscal budget burden. Moreover, a domestic water demand program to reduce per capita water demand is critically required. The programs may include conducting public awareness campaigns, upgrading the current water tariffs system, minimizing the UFW in the water supply system and to power the desalination technologies by renewable energy instead of fossil fuels.

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REFERENCES

- Abderrahman, W. A. 2001 *Energy and water in arid developing countries: Saudi Arabia, a case-study*. *International Journal of Water Resources Development* **17** (2), 247–255.
- Al-Ibrahim, A. 2013 *Seawater desalination: the strategic choice for Saudi Arabia*. *Desalination and Water Treatment* **51**, 1–4.
- Al-Karaghouli, A. & Kazmerski, L. L. 2013 *Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes*. *Renewable and Sustainable Energy Reviews* **24**, 343–356.
- Allan, T. 1997 'Virtual water': a long term solution for water short Middle Eastern economies? Paper presented at the 1997 British Association Festival of Science, Roger Stevens Lecture, (1997), University of Leeds, Water and Development Session- TUE.51.14.45, 9 September 1997.
- Al-Mutaz, I. S. 1987 *Water resources development in Riyadh, Saudi Arabia*. *Desalination* **64**, 193–202.
- Al-Mutaz, I. & Al-Namlah, A. 2004 Characteristic of dual purpose MSF desalination plants. *Desalination* **166** (2), 87–94.
- Almutaz, I., Ajbar, A. H. & Ali, E. 2012 Determinants of residential water demand in an arid and oil rich country: a case study of Riyadh city in Saudi Arabia. *International Journal of Physical Sciences* **7** (43), 5787–5796.
- Almutaz, I., Ali, E., Khalid, Y. & Ajbar, A. H. 2013 *A long-term forecast of water demand for a desalinated dependent city: case of Riyadh city in Saudi Arabia*. *Desalination and Water Treatment* **51**, 5934–5941.
- Al-Saud, M. I. 2010 Reduction of evaporation from water surfaces-preliminary assessment for Riyadh region, Kingdom of Saudi Arabia. *Research Journal of Soil and Water Management* **1**, 5–9.
- Al-Zahrani, M., Musa, A. & Chowdhury, S. 2015 *Multi-objective optimization model for water resource management: a case study for Riyadh, Saudi Arabia*. *Environment, Development and Sustainability* **18** (3), 777–798.
- Arbues, F., Garcia-Valinas, M. A. & Martinez-Espineira, R. 2003 *Estimation of residential water demand: a state of the art review*. *The Journal of Socio-Economics* **32**, 81–102.
- Banat, F. 2007 Economic and technical assessment of desalination technologies. Available at: <http://www.desline.com/Geneva/Banat.pdf> (accessed 12 September 2015).
- CDSI: Central Department of Statistics & Information 2010 Population and housing census for 1431 A.H (2010 A.D) Findings. Riyadh, KSA. Available at: <http://www.cdsi.gov.sa/> (accessed 10 January 2015).
- CDSI: Central Department of Statistics & Information 2014 *Statistical Year Book*. Fifty issue. Available at: <http://www.cdsi.gov.sa/yb50/YearBook.htm> (accessed 15 May 2015).
- Cheng, Q. & Chang, N. B. 2011 *System dynamics modeling for municipal water demand estimation in an urban region under uncertain economic impacts*. *Journal of Environmental Management* **92**, 1628–1641.
- Davis, W. Y. 2003 *Water Demand Forecast Methodology for California Water Planning Areas Work Plan and Model Review*. Research Report. California Bay-Delta Authority, CA.
- Demirbas, A., Rehan, M., Al-Sasi, B. O. & Nizami, A. S. 2016a *Evaluation of natural gas hydrates as a future methane source*. *Petroleum Science and Technology* **34** (13), 1204–1210.
- Demirbas, A., Bafail, A. & Nizami, A. S. 2016b *Heavy oil upgrading: unlocking the future fuel supply*. *Petroleum Science and Technology* **34** (4), 303–308.

- Demirbas, A., Al-Sasi, B. O. & Nizami, A. S. 2016c [Recent volatility in the price of crude oil](#). *Energy Sources, Part B: Economics, Planning, and Policy*. doi:10.1080/15567249.2016.1153751.
- El-Dessouky, H. T. & Ettouney, H. M. 2002 *Fundamentals of Salt Water Desalination*. Elsevier, Amsterdam.
- Foster, S. & Loucks, D. P. 2006 Non-renewable groundwater resources. IHP-VI, Series on groundwater no. 10. UNESCO, France. Available at: <http://unesdoc.unesco.org/images/0014/001469/146997E.pdf> (accessed 10 November 2016).
- Ghaffour, N., Missimer, T. M. & Amy, G. L. 2013 [Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability](#). *Desalination* **309**, 197–207.
- GW/IDR 2012 Technology choice still open at Yanbu 3, Water desalination report. Available at: <http://www.globalwaterintel.com/archive/13/10/general/technology-choice-still-open-yanbu-3.html> (accessed 8 June 2015).
- IAEA: International Atomic Energy Agency 2002 *Status of Design Concepts of Nuclear Desalination Plants*, IAEA-TECDOC-1326. Vienna, Austria.
- Ismail, I. M. I. & Nizami, A. S. 2016 Waste-based biorefineries in developing countries: an imperative need of time. In: *Paper presented at The Canadian Society for Civil Engineering: 14th International Environmental Specialty Conference*, London, Ontario, Canada, June 1–4. Available at: <http://ir.lib.uwo.ca/csce2016/London/Environmental/9/>.
- Jagannathan, N. V., Mohamed, A. S. & Kremer, A. 2009 *Water in the Arab World: Management Perspectives and Innovations*. World Bank, Washington, DC Available at: http://siteresources.worldbank.org/INTMENA/Resources/Water_Arab_World_full.pdf (accessed 15 March 2015).
- Khan, M. Z., Nizami, A. S., Rehan, M., Ouda, O. K. M., Sultana, S., Ismail, I. M. I. & Shahzad, K. 2017 [Microbial electrolysis cells for hydrogen production and wastewater treatment: a case study of Saudi Arabia](#). *Applied Energy* **185** (1), 410–420.
- Khatir, K. B. & Vairavamoorthy, K. 2009 Water demand forecasting for the city of the future against the uncertainties and the global change pressures: case of Birmingham. In *EWRI/ASCE, Conference, Kansas, USA*, May 17–21, 2009.
- Mabrouk, A. 2013 [Techno-economic analysis of tube bundle orientation for high capacity brine recycles MSF desalination plants](#). *Desalination* **320**, 24–32.
- Miandad, R., Rehan, M., Ouda, O. K. M., Khan, M. Z., Ismail, I. M. I., Shahzad, K. & Nizami, A. S. 2016a Waste-to-hydrogen energy in Saudi Arabia: challenges and perspectives. In: *Biohydrogen Production: Sustainability of Current Technology and Future Perspective* (A. Singh & D. Rathore, eds). Springer, India.
- Miandad, R., Barakat, M., Rehan, M., Ismail, I. M. I. & Nizami, A. S. 2016b The energy and value-added products from pyrolysis of waste plastics. In: *Recycling of Solid Waste for Biofuels and Bio-Chemicals* (O. P. Karthikeyan, ed.). Environmental footprints and eco-design of products and processes. Springer Science + Business Media, Singapore.
- Miandad, R., Barakat, M. A., Aburizaiza, A. S., Rehan, M. & Nizami, A. S. 2016c [Catalytic pyrolysis of plastic waste: a review](#). *Process Safety and Environmental Protection* **102**, 822–838.
- MOWE 2011 *Ministry of Water and Electricity*. Riyadh, Saudi Arabia.
- MWE: Ministry of Water and Electricity 2011 *Annual Report*. Riyadh, Saudi Arabia. Available at: <http://www.mowe.gov.sa/ENIndex.aspx> (accessed 22 June 2015).
- MWE: Ministry of Water and Electricity 2012 *Supporting Documents for King Hassan II Great World Water Prize*. Riyadh, KSA.
- Napoli, C. & Rioux, B. 2016 [Evaluating the economic viability of solar-powered desalination: Saudi Arabia as a case study](#). *International Journal of Water Resources Development* **32** (3), 412–427.
- Nizami, A. S. & Ismail, I. M. I. 2013 [Life-Cycle Assessment of Biomethane From Lignocellulosic Biomass](#). Life cycle assessment of renewable energy sources Springer-Verlag, London. DOI: 10.1007/978-1-4471-5364-1_4.
- Nizami, A. S., Rehan, M., Gardy, J., Hassanpour, A., Iqbal, T. & Ismail, I. M. 2014 [The potential of natural zeolites in energy recovery technology from waste plastic](#). In: *The 7th International Conference on Sustainable Energy & Environmental Protection (SEEP), the British University in Dubai, UAE*, November 23–25, 2014. DOI: 10.13140/2.1.1227.1680.
- Nizami, A. S., Rehan, M., Ouda, O. K. M., Shahzad, K., Sadeq, Y., Iqbal, T. & Ismail, I. M. I. 2015a An argument for developing waste-to-energy technologies in Saudi Arabia. *Chemical Engineering Transactions* **45**, 337–342.
- Nizami, A. S., Rehan, M., Ismail, I. M. I., Almeelbi, T. & Ouda, O. K. M. 2015b [Waste biorefinery in Makkah: a solution to convert waste produced during Hajj and Umrah Seasons into wealth](#). In: *15th Scientific Symposium for Hajj, Umrah and Madinah Visit. Madinah, Saudi Arabia*. doi:10.13140/RG.2.1.4303.6560.
- Nizami, A. S., Ouda, O. K. M., Rehan, M., El-Maghraby, A. M. O., Gardy, J., Hassanpour, A., Kumar, S. & Ismail, I. M. I. 2016a [The potential of Saudi Arabian natural zeolites in energy recovery technologies](#). *Energy* **108**, 162–171.
- Nizami, A. S., Mohanakrishna, G., Mishra, U. & Pant, D. 2016b [Trends and Sustainability Criteria for the Liquid Biofuels. Biofuels: Production and Future Perspectives](#). CRC Press, Boca Raton, FL, pp. 59–95. DOI: 10.1201/9781315370743-1.
- Nizami, A. S., Shahzad, K., Rehan, M., Ouda, O. K. M., Khan, M. Z., Ismail, I. M. I., Almeelbi, T., Basahi, J. M. & Demirbas, A. 2017 [Developing waste biorefinery in Makkah: a way forward to convert urban waste into renewable energy](#). *Applied Energy* **186** (2), 189–196.
- Ouda, O. K. M. 2013a Review of Saudi Arabia municipal water tariff. *World Environment* **3** (2), 66–70.
- Ouda, O. K. M. 2013b Towards assessment of Saudi Arabia public awareness of water shortage problem. *Resources and Environment* **3** (1), 10–15.

- Ouda, O. K. M. 2014a *Impacts of agricultural policy on irrigation water demand: case study Saudi Arabia*. *International Journal of Water Resources Development* **30** (2), 282–292.
- Ouda, O. K. M. 2014b *Water demand versus supply in Saudi Arabia: current and future challenges*. *International Journal of Water Resources Development* **30** (2), 335–344.
- Ouda, O. K. M. 2015 *Treated wastewater use in Saudi Arabia: challenges and initiatives*. *International Journal of Water Resources Development* **32** (5), 799–809.
- Ouda, O. K. M., Shawesh, A., Al-Olabi, T., Younes, F. & Al-Waked, R. 2013 *Review of domestic water conservation practices in Saudi Arabia*. *Applied Water Science* **3**, 689–699.
- Ouda, O. K. M., Al-Waked, R. & Al-Shehri, A. A. 2014 *Privatization of water supply services in Saudi Arabia: a unique experience*. *Utilities Policy* **31**, 107–113.
- Ouda, O. K. M., Raza, S. A., Nizami, A. S., Rehan, M., Al-Waked, R. & Korres, N. E. 2016 *Waste to energy potential: a case study of Saudi Arabia*. *Renewable and Sustainable Energy Reviews* **61**, 328–340.
- Rahmanian, N., Ali, S. H. B., Homayoonfard, M., Ali, N. J., Rehan, M., Sadeh, Y. & Nizami, A. S. 2015 *Analysis of physiochemical parameters to evaluate the drinking water quality in the state of Perak, Malaysia*. *Journal of Chemistry* **2015**, Article ID 716125, 1–10.
- Raluy, R. G., Serra, L. & Valero, J. U. A. 2004 *Life-cycle assessment of desalination technologies integrated with energy production systems*. *Desalination* **167**, 445–458.
- Rathore, D., Nizami, A. S., Pant, D. & Singh, A. 2016 *Key issues in estimating energy and greenhouse gas savings of biofuels: challenges and perspectives*. *Biofuel Research Journal* **10**, 380–393.
- Rehan, M., Nizami, A. S., Shahzad, K., Ouda, O. K. M., Ismail, I. M. I., Almeelbi, T., Iqbal, T. & Demirbas, A. 2016 *Pyrolytic liquid fuel: a source of renewable energy in Makkah*. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* **38** (17), 2598–2603.
- Sadeh, Y., Nizami, A. S., Batool, S. A., Chaudhary, M. N., Ouda, O. K. M., Asam, Z. Z., Habib, K., Rehan, M. & Demibras, A. 2016 *Waste-to-energy and recycling value for developing integrated solid waste management plan in Lahore*. *Energy Sources, Part B: Economics, Planning, and Policy* **11** (7), 569–579.
- Schiffler, M. 2004 *Perspectives and challenges for desalination in the 21st century*. *Desalination* **165**, 1–9.
- SGS: Saudi Geological Survey 2012 *Kingdom of Saudi Arabia Numbers and Facts, Saudi Geographical Survey*, 1st edn. Riyadh, KSA.
- Shahzad, K., Rehan, M., Ismail, I. M. I., Sagir, M., Tahir, M. S., Bertok, B. & Nizami, A. S. 2015 *Comparative life cycle analysis of different lighting devices*. *Chemical Engineering Transactions* **45**, 631–636.
- Shahzad, K., Čučekb, L., Sagir, M., Nizami, A. S., Tariq, I., Almeelbia, T. & Ismail, I. M. I. 2016 *A case study for developing eco-efficient street lighting system in Saudi Arabia*. *Chemical Engineering Transactions* **52**, 1141–1146.
- Sommariva, C., Hogg, H. & Callister, K. 2001 *Forty-year design life: the next target material selection and operating conditions in thermal desalination plants*. *Desalination* **136**, 169–176.
- Strathmann, H. 1992 *Electrodialysis*. In: *Membrane Handbook* (W. S. W. Ho & K. K. Sirkar, eds). Van Nostrand Reinhold, New York.
- SWCC 2010 *Annual Report for Operation & Maintenance*. Saline Water Conservation Corporation, Riyadh, KSA.
- SWCC 2011 *Annual Report*, no. 38, Saline Water Conservation Corporation, Riyadh, KSA, pp. 16–23.
- Tsiourtis, N. X. 2008 *Criteria and procedure for selecting a site for a desalination plant*. *Desalination* **221**, 114–125.
- UNDP: United Nations Development Programme 2013 *Water Governance in the Arab Region: Managing Scarcity and Securing the Future*. New York.
- Water Technology 2015 *Ras Al-Khair desalination plant, Saudi Arabia*. Available at: <http://www.water-technology.net/projects/ras-al-khair-desalination-plant/> (accessed 2 December 2015).
- Wilf, M., Awerbuch, L., Bartels, C., Mickley, M., Pearce, G. & Voutchkov, N. 2007 *The Guidebook to Membrane Desalination Technology*. Balaban Desalination Publications, L'Aquila, Italy.
- World Bank 2004 *Kingdom of Saudi Arabia, Assessment of the Current Water Resource Management Situation*. Phase I, Vol. 1. World Bank, Washington, DC.
- World Bank 2005 *A Water Sector Assessment Report on Countries of the Cooperation Council of the Arab State of the Gulf*. Report No. 32539-MNA. World Bank, Washington, DC.
- World Bank 2010 *Making the Most of Scarcity: Accountability for Better Water Management Results in the Middle East and North Africa Report*. World Bank, Washington, DC.
- Worthington, A. C. & Hoffman, M. 2007 *A State of the Art Review of Residential Water Demand Modelling*. School of Accounting & Finance, University of Wollongong, Working Paper 6.